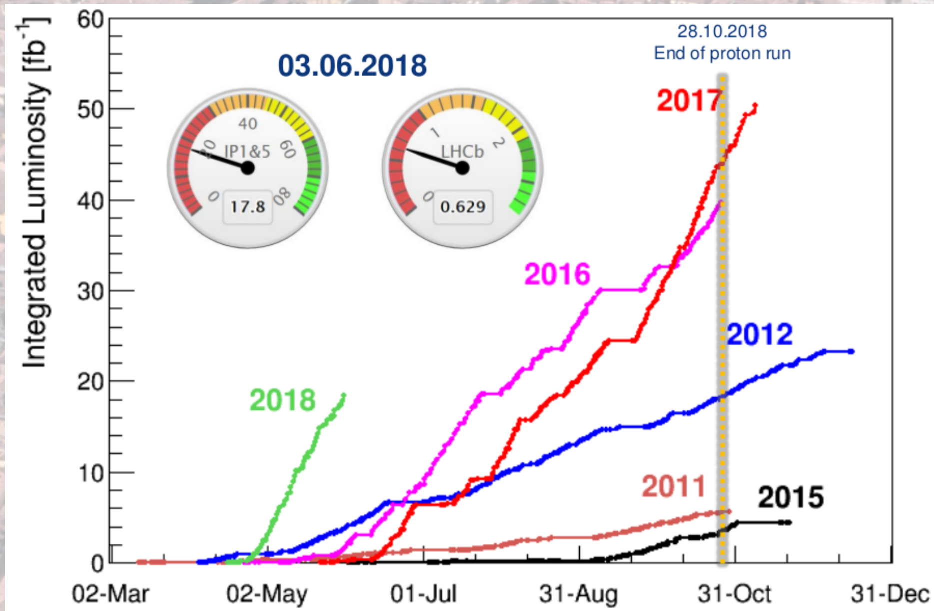
Bologna 2018

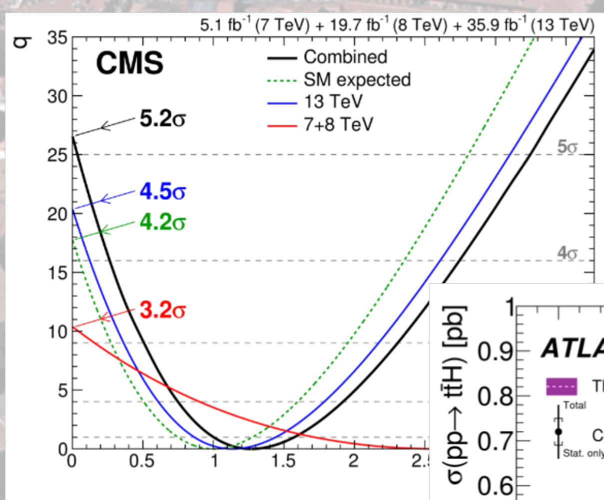
Sixth Conference on Large Hadron Collider Physics

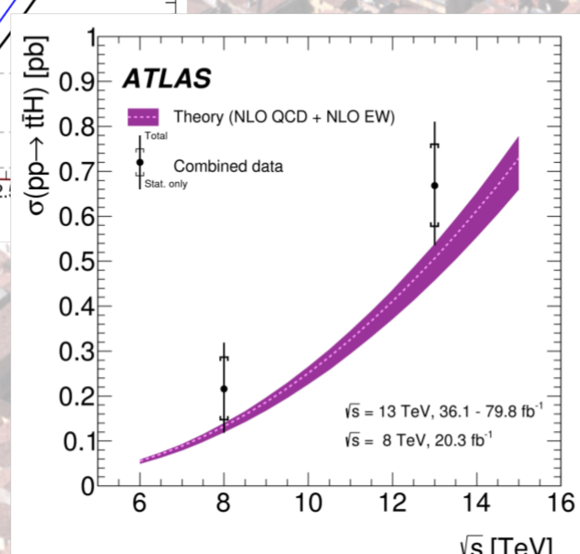
Top Quark Physics

Markus Schulze

Humboldt-University Berlin





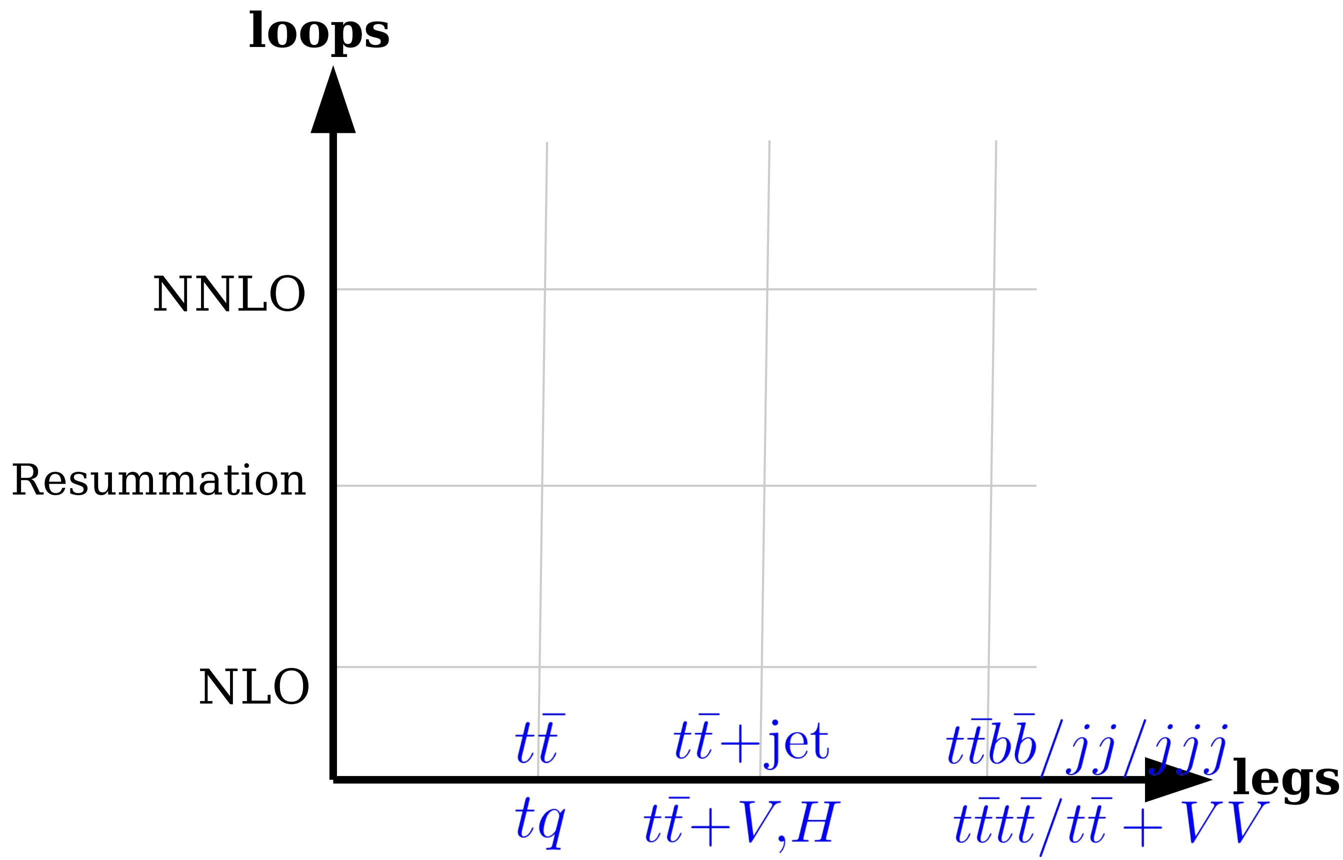


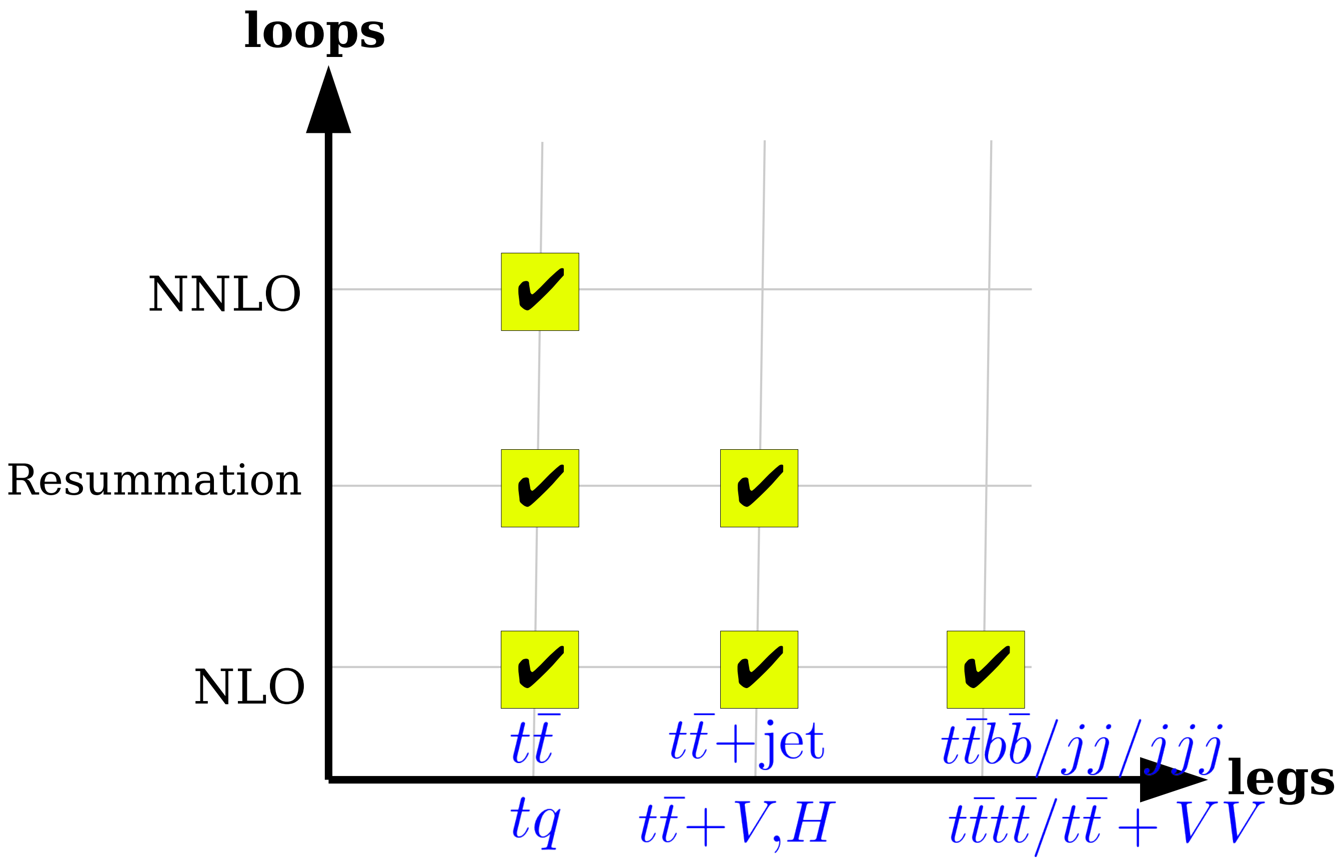
- **The LHC is in full swing**
- **Expecting >150 fb^{-1} (run1+2)**
  >300 fb^{-1} (run1+2+3)
- **Impressive results by experimental collaborations**
- **Challenge in the years to come:**
  Precision and *subtle effects*

  Leave no stone unturned.
- **Top quark physics is one of the most prominent places to search for New Physics**

Part 1: State-of-the-Art

Part 2: Physics Impact on SM and BSM


loops
NNLO
Resummation
NLO
$t\bar{t}$
tq
$t\bar{t}$+jet
$t\bar{t}$+V,H
$t\bar{t}b\bar{b}/jj/jjj$
$t\bar{t}t\bar{t}/t\bar{t}+VV$
legs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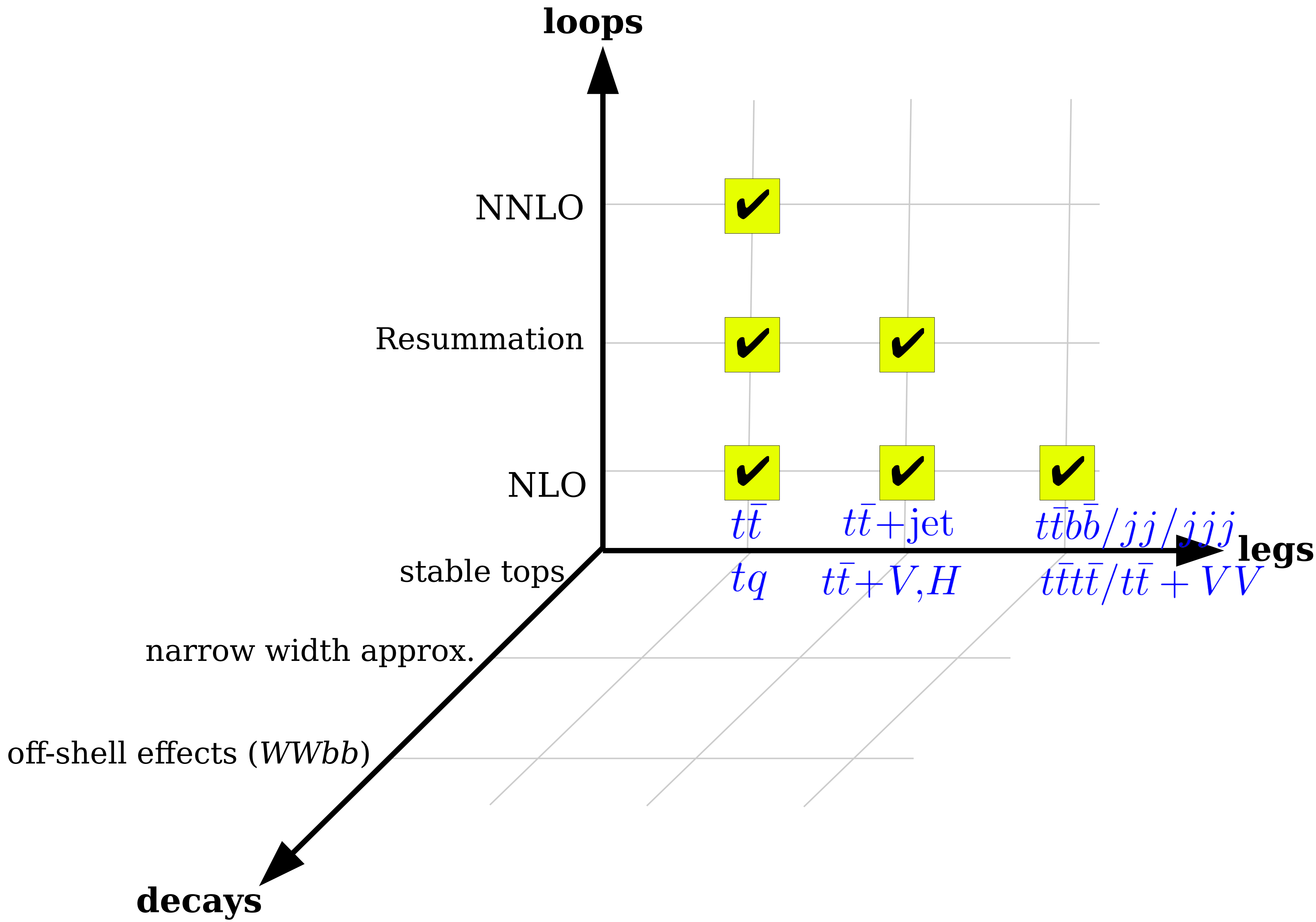
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stable tops
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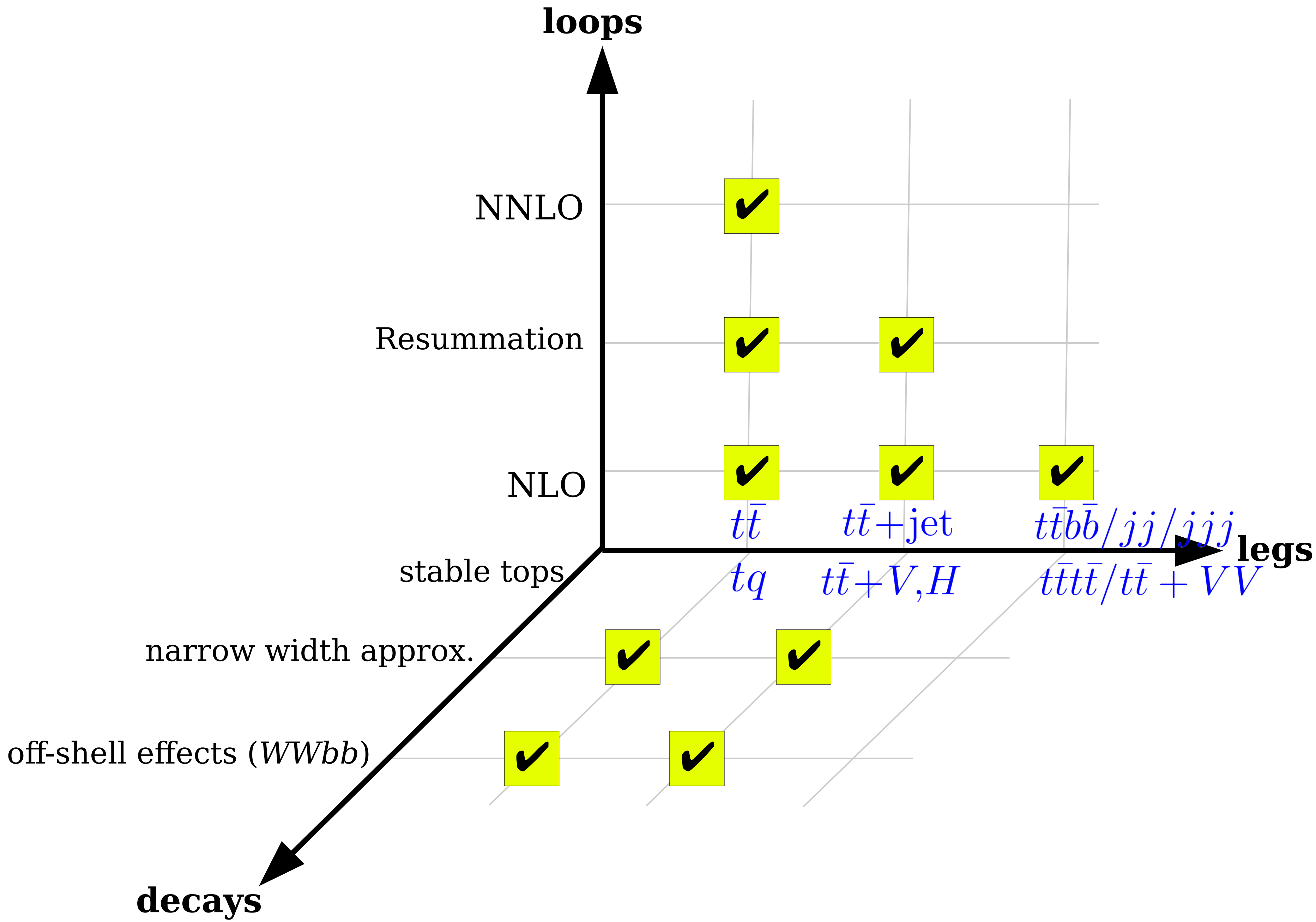
narrow width approx.
off-shell effects ($WWbb$)
decays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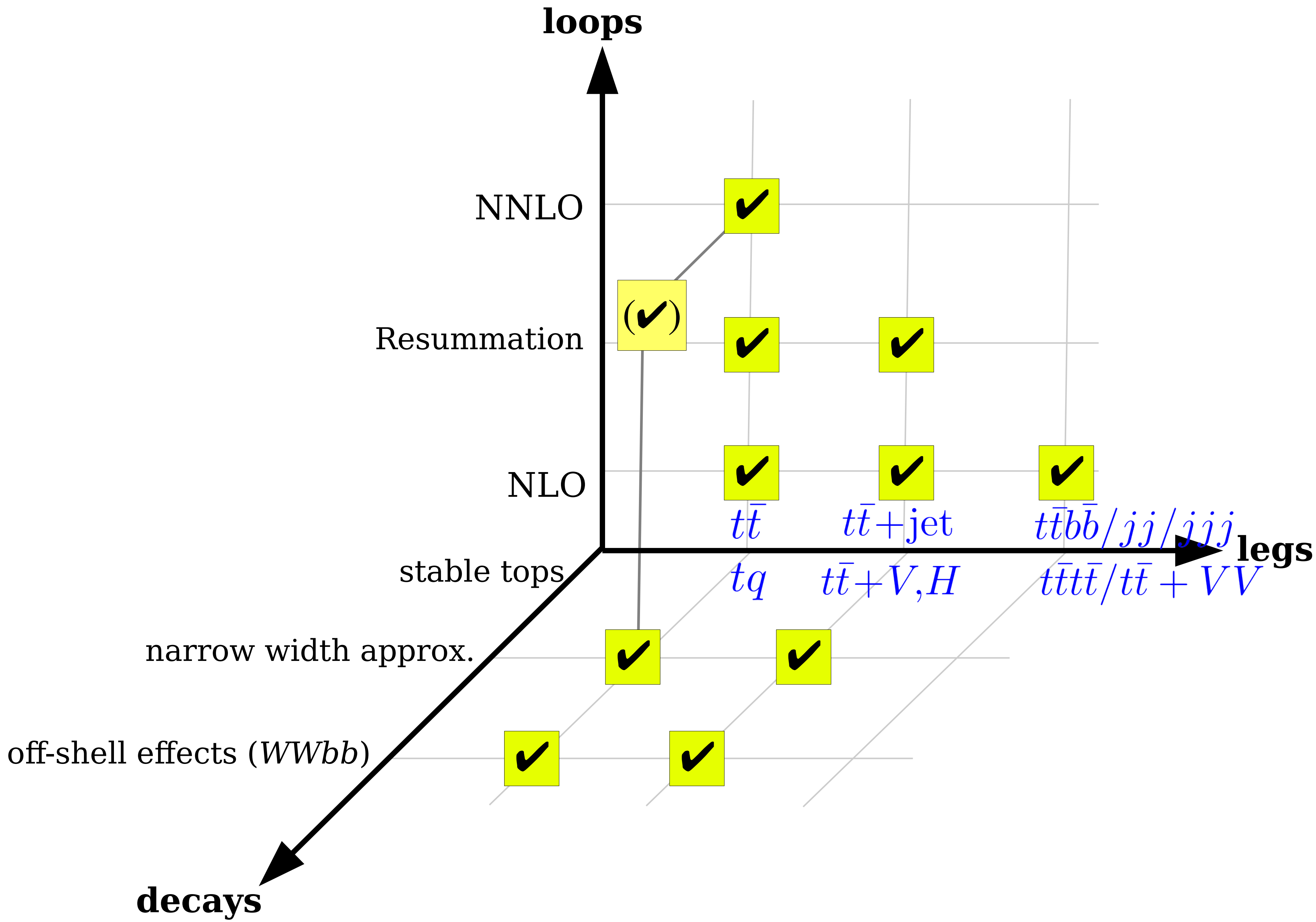

loops
NNLO
Resummation
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(✔)
✔
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NNLO QCD + NLO electroweak corrections

Journal of High Energy Physics
October 2017, 2017:186 | Cite as

Top-pair production at the LHC through NNLO QCD and NLO EW

Authors | Authors and affiliations

Michał Czakon, David Heymes, Alexander Mitov, Davide Pagani , Ioannis Tsinikos, Marco Zaro

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Uncertainties	
scale	± 3%
pdf	± 2%
alpha_s	± 1%
m_top	± 3%
electroweak	± 2%

First NNLO QCD correction:
[Czakon,Fiedler,Mitov] (2013)

First NLO weak corrections:
[Beenakker,Denner,Hollik, Mertig,Sack,Wackeroth] (1993)
[Kühn,Scharf,Uwer] (2007)
[Bernreuther,Fucker,Si] (2008)

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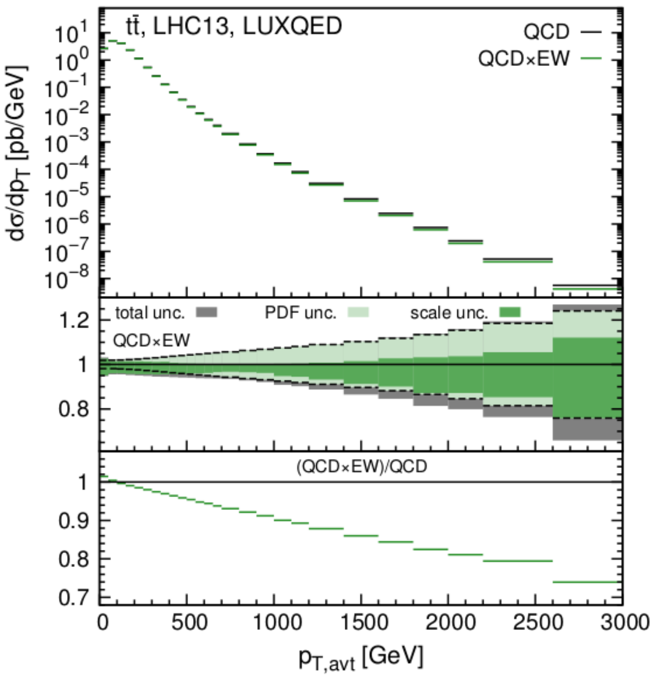
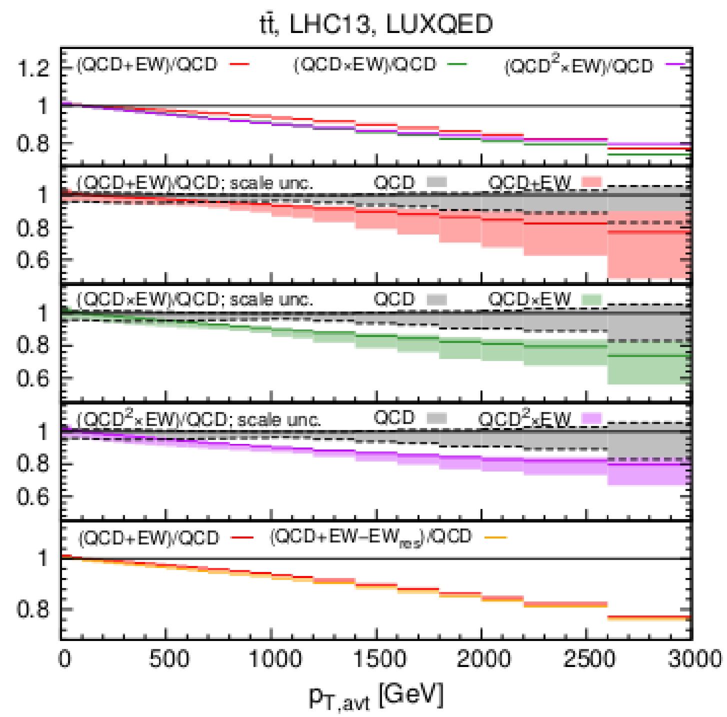
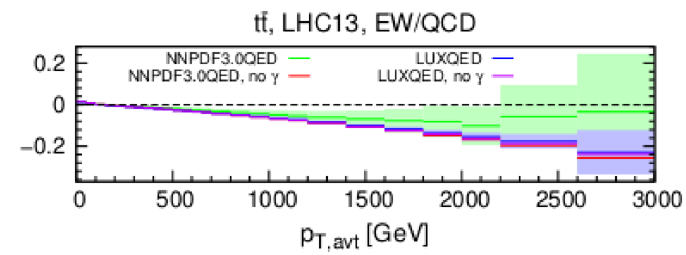
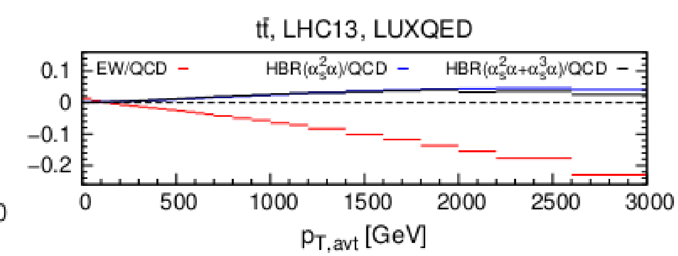








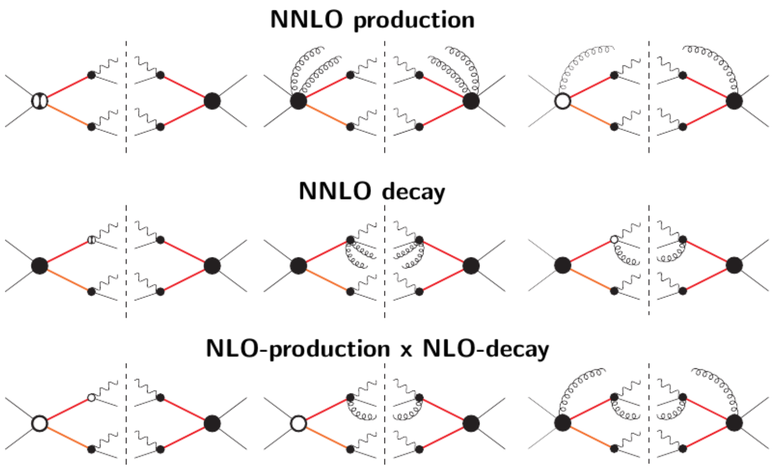
- Electroweak Sudakov suppression: −20% at p_T=2 TeV
- Photon initial states: Very small contribution
- Real emission of *Z*/*W*-Bosons: only ~ +3% at large p_T

Towards NNLO QCD with top quark decays

PHYSICAL REVIEW D **96**, 051501(R) (2017)

Top-quark pair-production and decay at high precision

Jun Gao[1] and Andrew S. Papanastasiou[2]



- Includes **NNLO decay** through spin-correlated Narrow-Width-Approximation $\mathcal{O}(\Gamma_t/m_t)$
- **Approximate NNLO production correction** from SCET-based soft-gluon resummation [Ahrens,Ferroglia,Neubert,Pecjak,Yang] (2010)

Towards NNLO QCD with top quark decays

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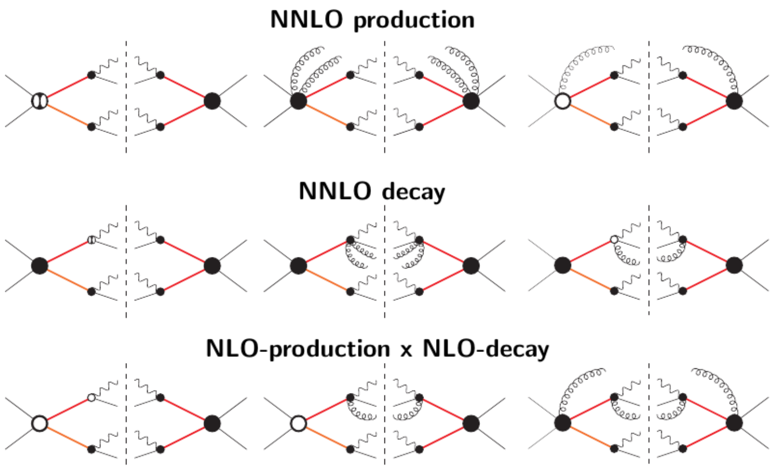

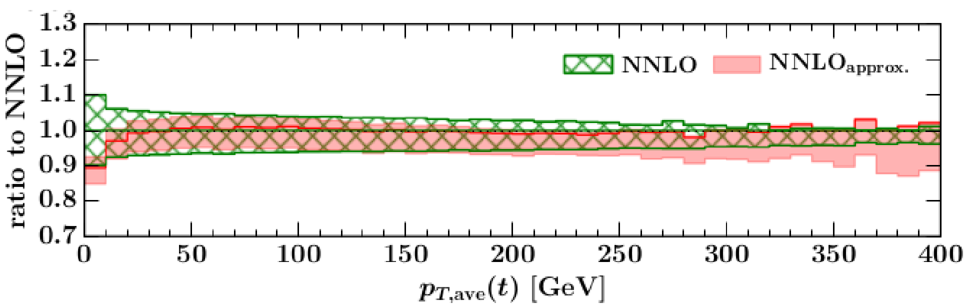

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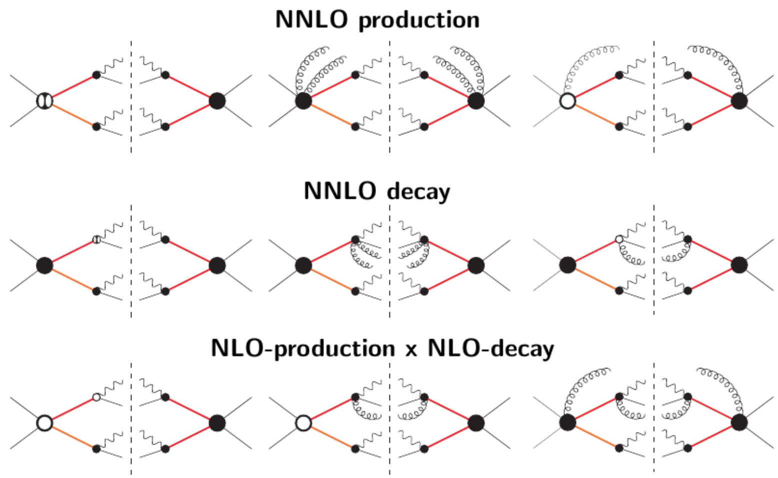

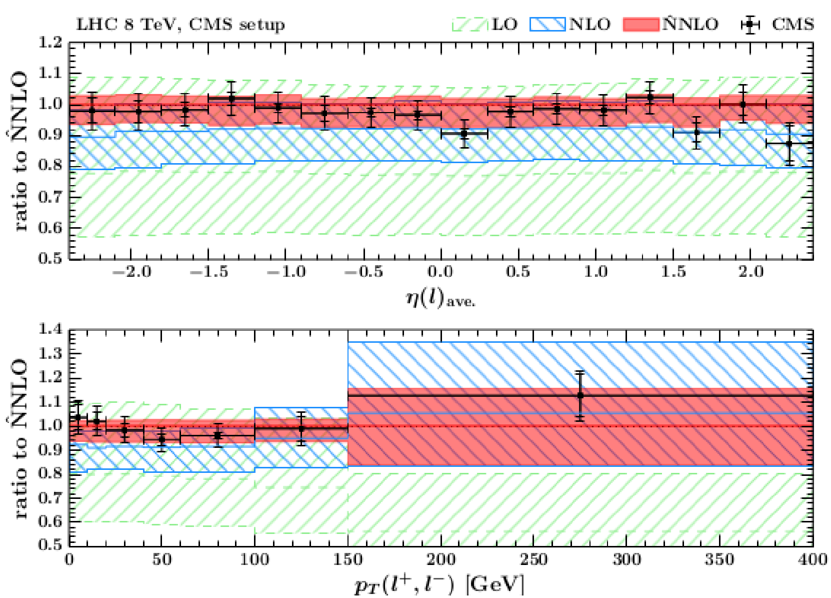

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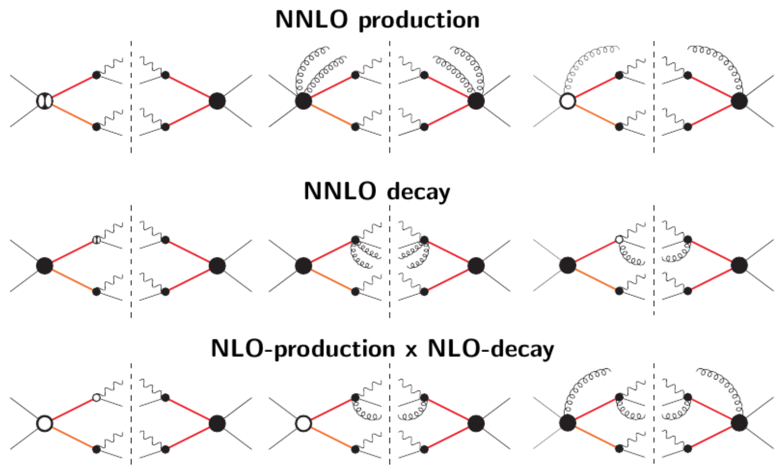
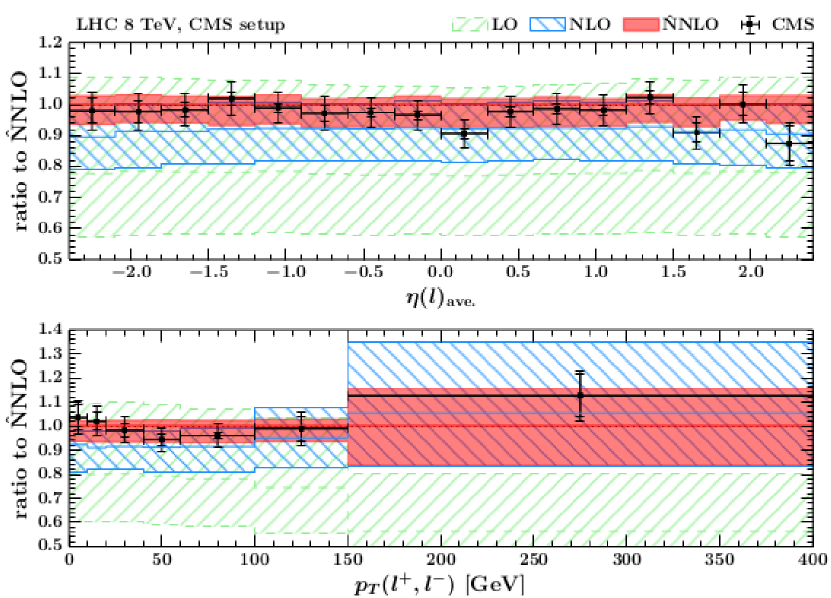




Journal of High Energy Physics
March 2018, 2018:85 | Cite as

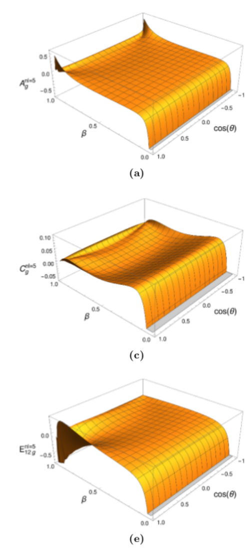
Polarized double-virtual amplitudes for heavy-quark pair production

Authors Authors and affiliations

L. Chen, M. Czakon, R. Poncelet

$$\mathcal{R}^{\text{2-loop}}_{q,g} = \frac{1}{4}\,\mathrm{Tr}\left[R^{q,g}(\mathbf{1}+\hat{\mathbf{s}}_t\sigma)\otimes(\mathbf{1}+\hat{\mathbf{s}}_{\bar{t}}\sigma)\right]\Big|_{\text{2-loop}}$$

$$\begin{aligned}\mathcal{R}^{\text{2-loop}}_{q,g} = {} & A_{q,g} + (B)_{q,g}\left(\epsilon^{\mu\nu\alpha\beta}p_{1\mu}p_{2\nu}p_{3\alpha}s_{t\beta} + \epsilon^{\mu\nu\alpha\beta}p_{1\mu}p_{2\nu}p_{3\alpha}s_{\bar{t}\beta}\right)\\ & + (C)_{q,g}\left((s_t\cdot s_{\bar{t}})\right) + (D)_{q,g}\left((p_1\cdot s_t)(p_1\cdot s_{\bar{t}}) + (p_2\cdot s_t)(p_2\cdot s_{\bar{t}})\right)\\ & + (E_{12})_{q,g}\left((p_1\cdot s_t)(p_2\cdot s_{\bar{t}})\right) + (E_{21})_{q,g}\left((p_2\cdot s_t)(p_1\cdot s_{\bar{t}})\right).\end{aligned}$$



- Numerical interpolation grid with thresh. and HE-expansion
- Full spin and color information
- Provides spin-density matrix

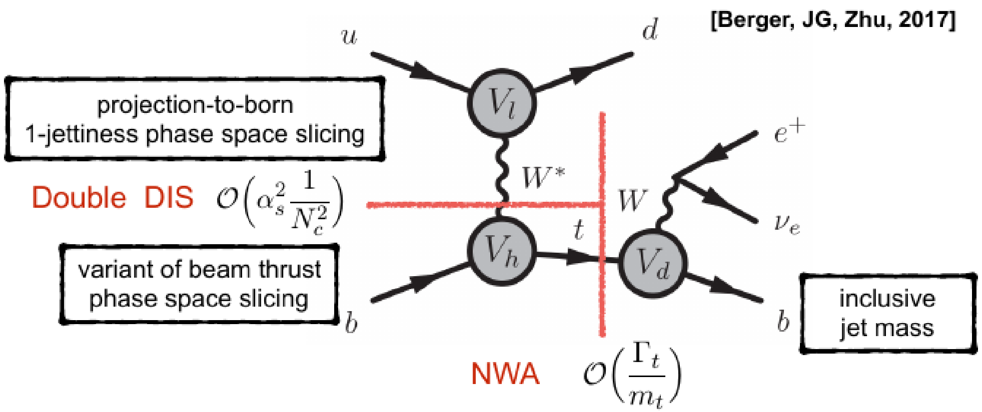
Single top quark production + decay at NNLO QCD

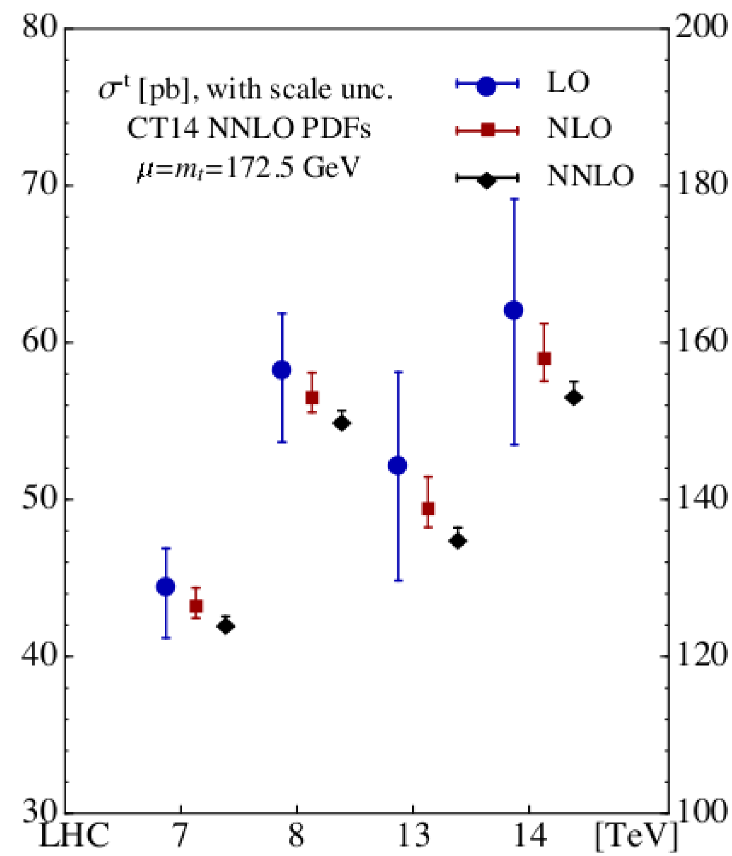
NNLO QCD corrections to t-channel single top quark production and decay

Edmond L. Berger, Jun Gao, C.-P. Yuan, and Hua Xing Zhu
Phys. Rev. D **94**, 071501(R) – Published 4 October 2016

First NNLO production calculation:
[Brucherseifer, Caola, Melnikov] (2014)

First NNLO top decay calculation:
[Gao,Li,Zhu] (2012)





Single top quark production + decay at NNLO QCD

Journal of High Energy Physics
November 2017, 2017:158 | Cite as

Differential distributions for t-channel single top-quark production and decay at next-to-next-to-leading order in QCD

Authors Authors and affiliations
Edmond L. Berger, Jun Gao, Hua Xing Zhu

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[Brucherseifer, Caola, Melnikov] (2014)

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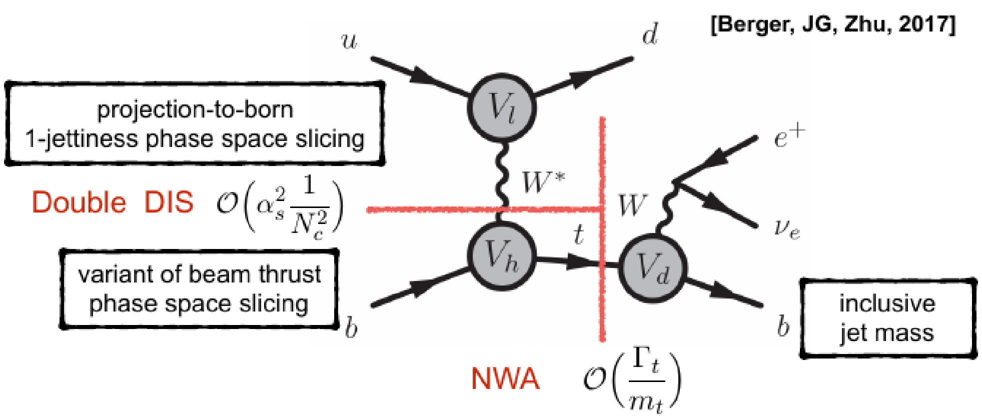
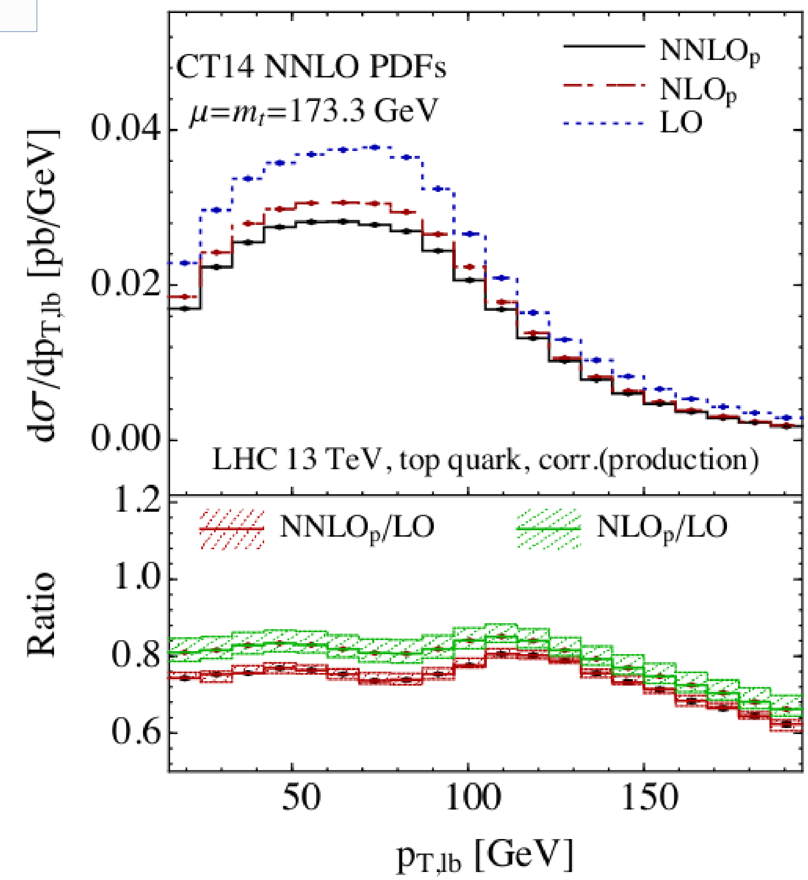




- First fully differential calculation for top quarks with production and decay at NNLO QCD

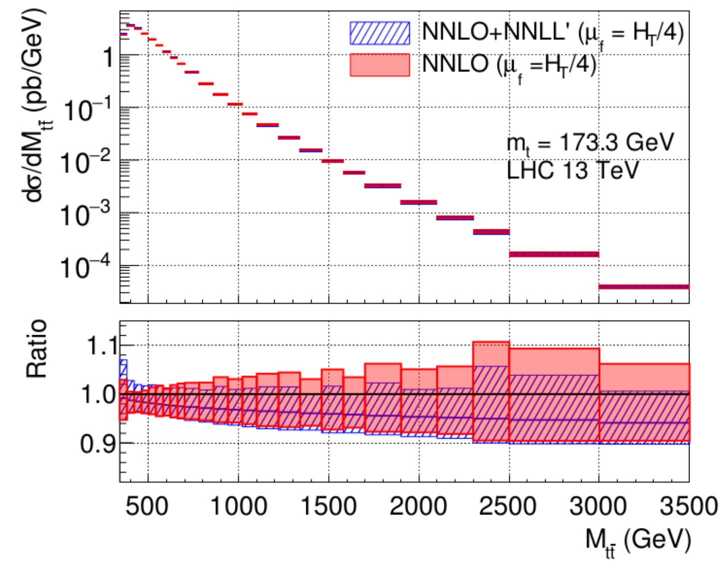
Resummation

Journal of High Energy Physics
May 2018, 2018:149 | Cite as

Resummation for (boosted) top-quark pair production at NNLO+NNLL' in QCD

Authors | Authors and affiliations

Michal Czakon, Andrea Ferroglia, David Heymes, Alexander Mitov, Ben D. Pecjak, Darren J. Scott, Xing Wang, Li Lin Yang



$$\text{soft limit:} \quad \hat{s}, |t_1|, m_t^2 \gg \hat{s}(1-z)^2\,,$$

$$\text{boosted-soft limit:} \quad \hat{s}, |t_1| \gg m_t^2 \gg \hat{s}(1-z)^2 \gg m_t^2(1-z)^2$$

	$\Gamma^i_{\rm cusp}$, β	γ^h, γ^S, γ^ϕ	$\boldsymbol{H}^{(m)}$, $\widetilde{\boldsymbol{s}}^{(m)}$, C_D, $\widetilde{s}_D$	$\alpha_s^n L^k$
NLL	NLO	LO	LO	$2n-1 \le k \le 2n$
NNLL	NNLO	NLO	NLO	$2n-3 \le k \le 2n$
NNLL′	NNLO	NLO	NNLO	$2n-4 \le k \le 2n$

Table 1. Our naming scheme for the logarithmic accuracies. We list the perturbative orders at which the cusp anomalous dimension, the QCD β-function, all other anomalous dimensions and matching functions need to be evaluated in order to obtain resummation at a given logarithmic order.

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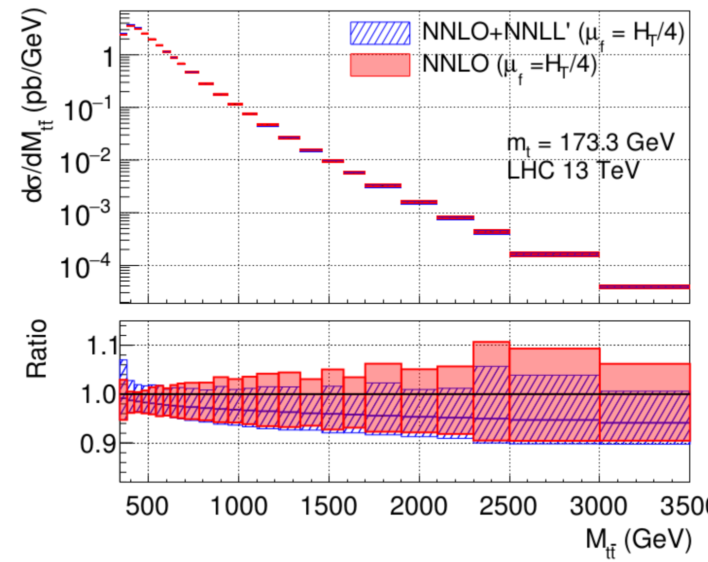

- Note: *Boosted-soft resummation* is the small-mass limit of *soft gluon resummation*

Resummation

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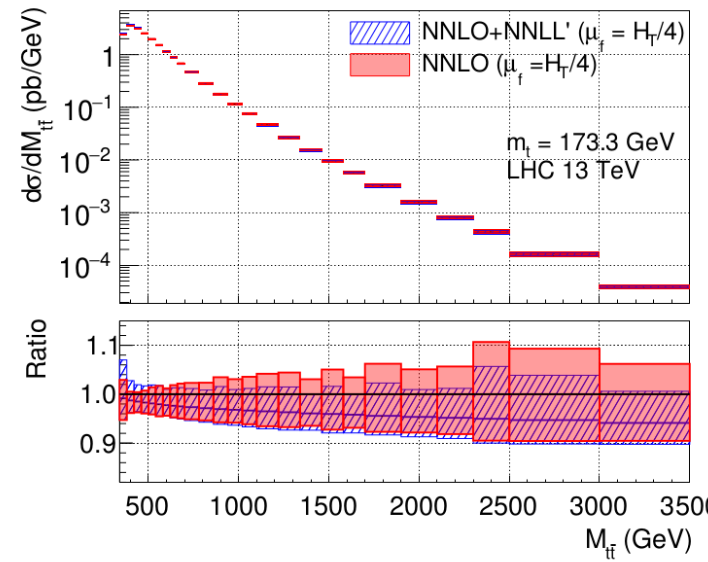

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(June 2018)

Transverse-momentum resummation for top-quark pair production at the LHC

Stefano Catani[(a)], Massimiliano Grazzini[(b)] and Hayk Sargsyan[(b)]

Resummation

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May 2018, 2018:149 | Cite as

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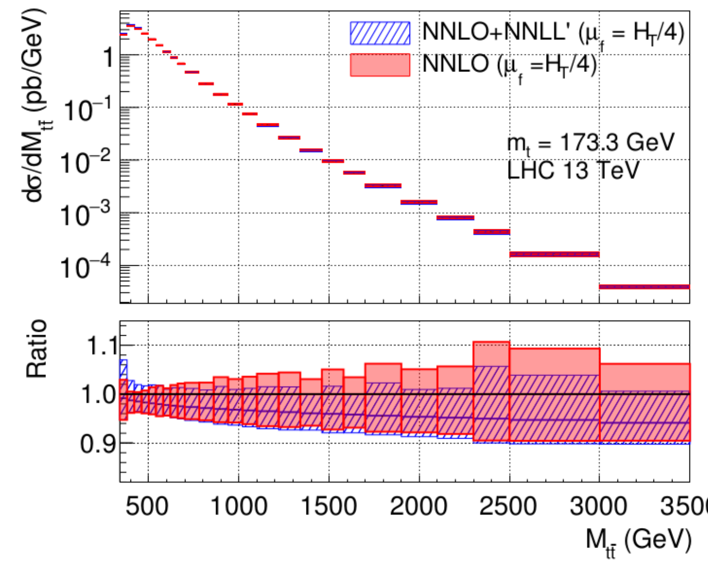

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(June 2018)

Transverse-momentum resummation for

S ... n[(b)]

MINLO t-channel single-top plus jet

(May 2018)

Stefano Carrazza,[a] Rikkert Frederix,[b] Keith Hamilton,[a,c] Giulia Zanderighi[a,*]

Resummation

[Journal of High Energy Physics](#)
May 2018, 2018:149 | Cite as

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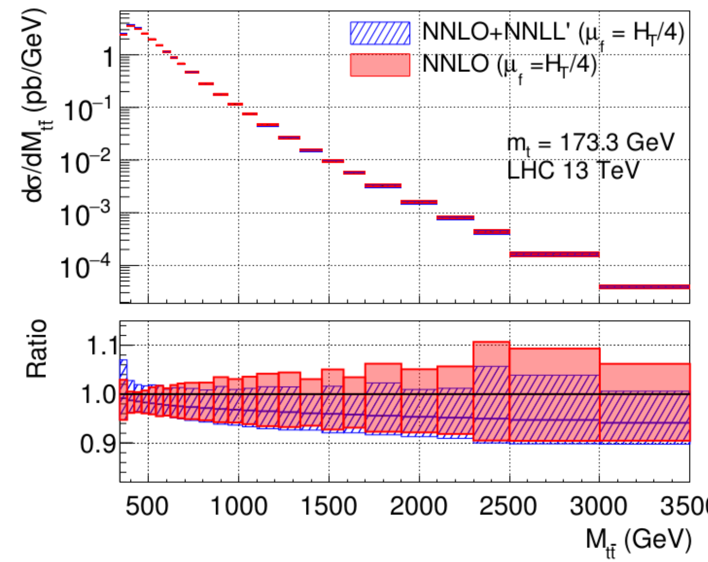

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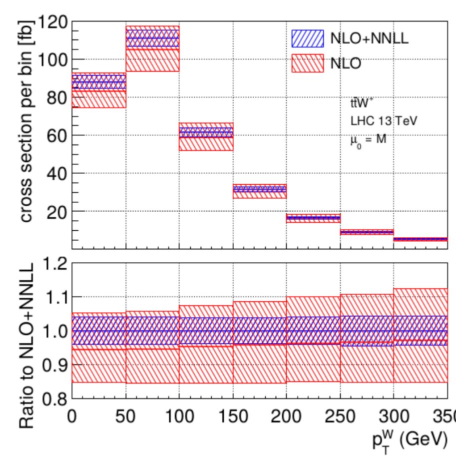
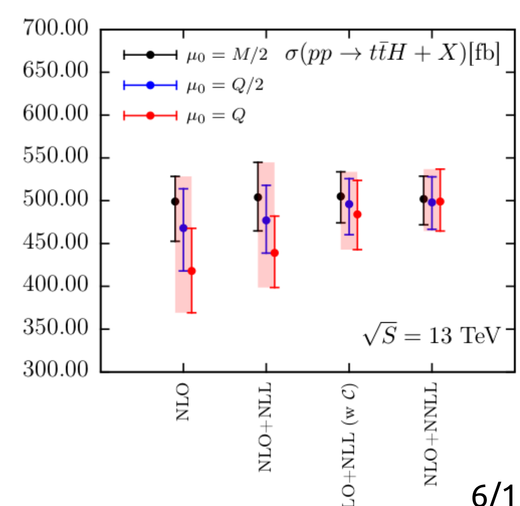
Resummation for $t\bar{t}+X$:

$t\bar{t}+H$: [Kulesza, Motyka, Stebel, Theeuwes] (2017)
[Broggio, Ferroglia, Fiolhais, Onofre] (2017)

$t\bar{t}+W$: [Kulesza, Motyka, Schwartländer, Stebel, Theeuwes] (2017)
[Broggio, Ferroglia, Ossola, Pecjak] (2016)

$t\bar{t}+Z$: [Broggio, Ferroglia, Ossola, Pecjak, Samshima] (2017)





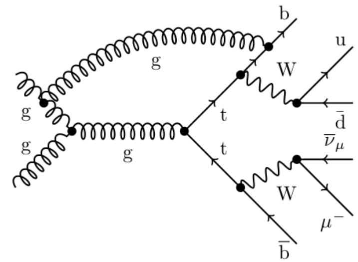
Off-shell calculations

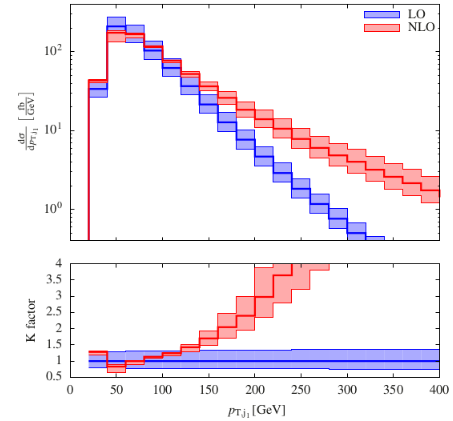

Journal of High Energy Physics
February 2018, 2018:13 | Cite as

Off-shell production of top-antitop pairs in the lepton+jets channel at NLO QCD

Authors   Authors and affiliations

Ansgar Denner, Mathieu Pellen





- extends previous off-shell calculations through L+J channel

Off-shell calculations

Journal of High Energy Physics
February 2018, 2018:13 | Cite as

Off-shell production of top-antitop pairs in the lepton+jets channel at NLO QCD

Authors | Authors and affiliations

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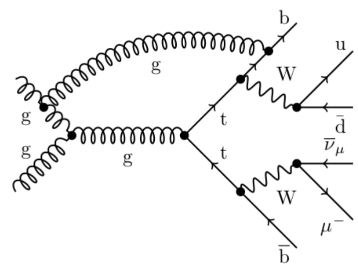

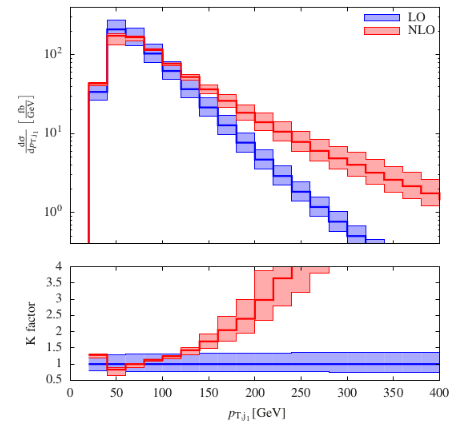

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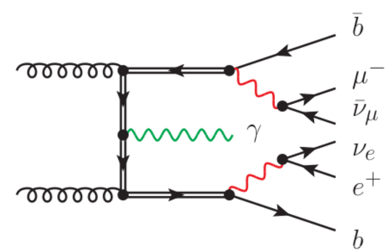
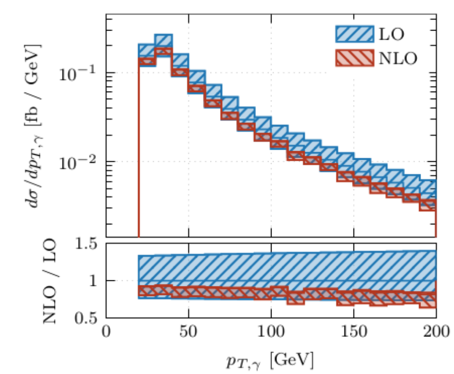
(Dec 2017) TTK-18-09, HU-EP-18/07, IPPP/18/17

Hard Photons in Hadroproduction of Top Quarks with Realistic Final States

G. Bevilacqua[a], H. B. Hartanto[b], M. Kraus[c], T. Weber[d] and M. Worek[d]





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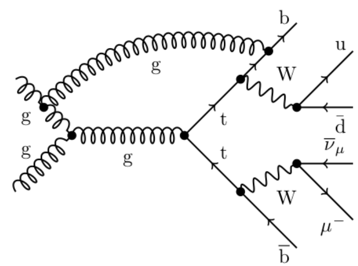

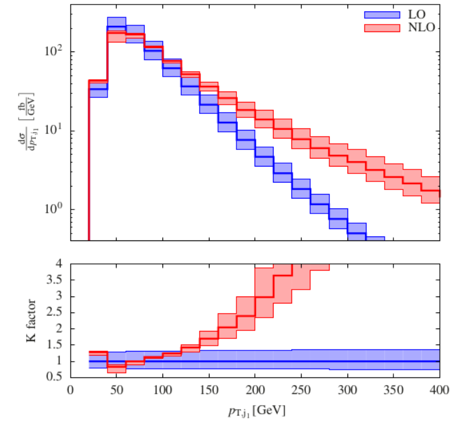

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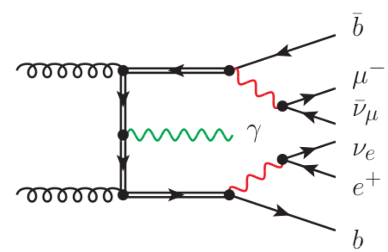
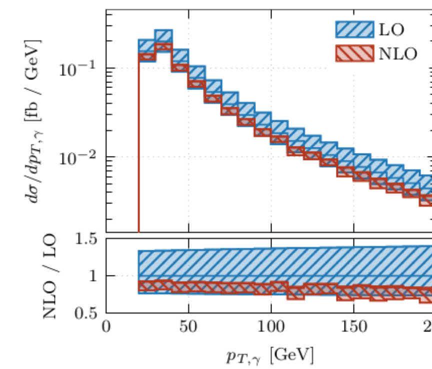




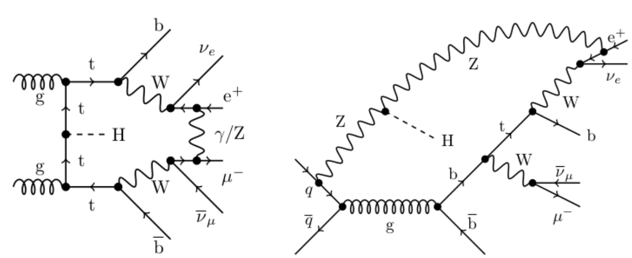
- extends previous calculation in the narrow-width approximation

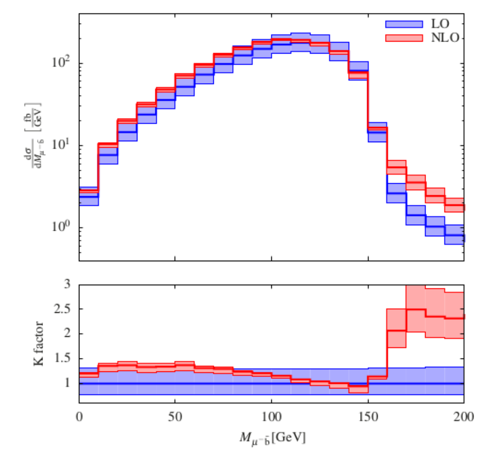
Journal of High Energy Physics
February 2017, 2017:53 | Cite as

Higgs production in association with off-shell top-antitop pairs at NLO EW and QCD at the LHC

Authors   Authors and affiliations

Ansgar Denner, Jean-Nicolas Lang, Mathieu Pellen, Sandro Uccirati





- extends previous calculation in the narrow-width approximation

Part 1: State-of-the-Art

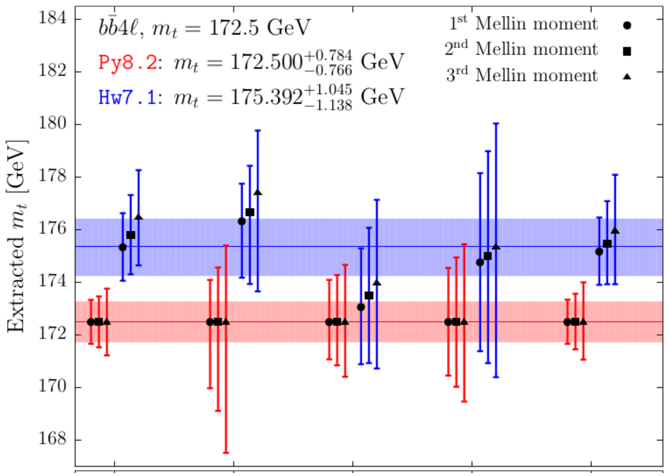
Part 2: Physics Impact on SM and BSM

Top quark mass

A Theoretical Study of Top-Mass Measurements at the LHC Using NLO+PS Generators of Increasing Accuracy

(Jan 2018)

Silvia Ferrario Ravasio,[a] **Tomáš Ježo,**[b] **Paolo Nason,**[c] **Carlo Oleari**[a]



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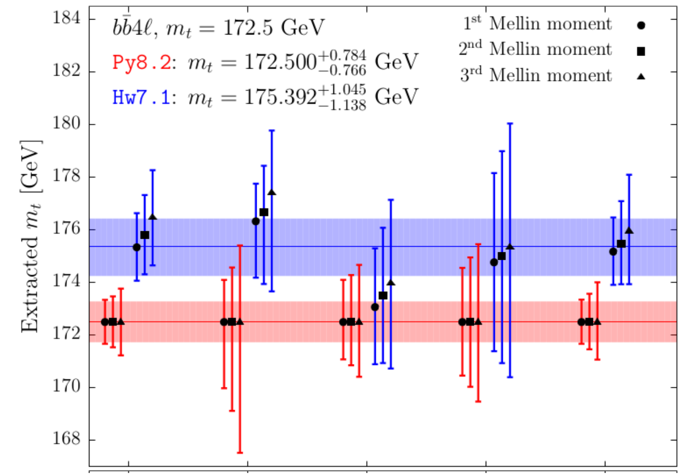
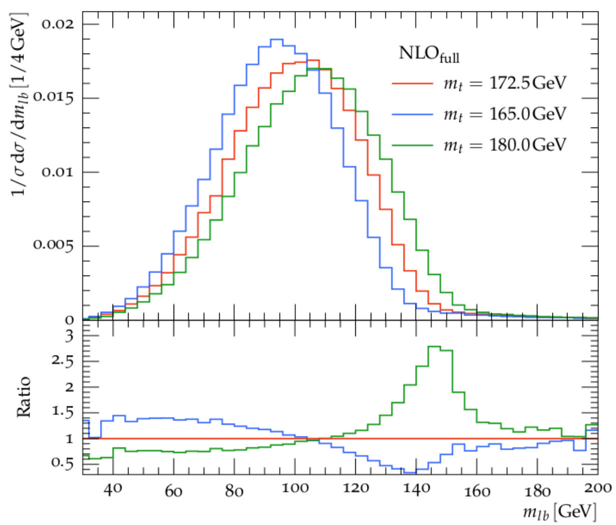
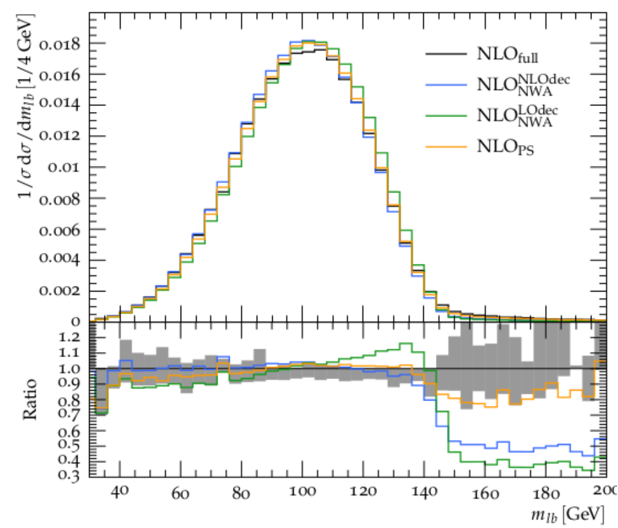


NLO and off-shell effects in top quark mass determinations

(Sep 2017)

Gudrun Heinrich,[a] Andreas Maier,[b] Richard Nisius,[a] Johannes Schlenk,[c] Markus Schulze,[d] Ludovic Scyboz,[a] Jan Winter [e]





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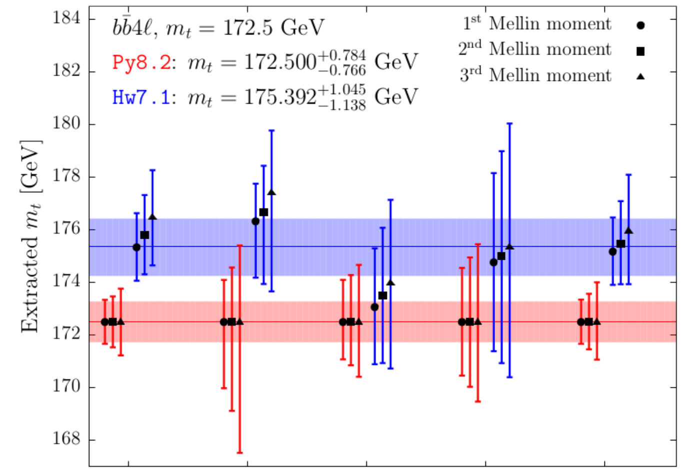

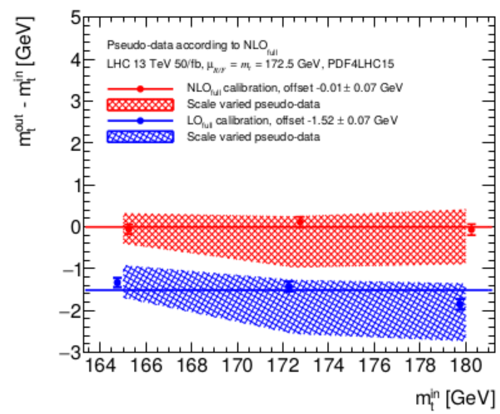

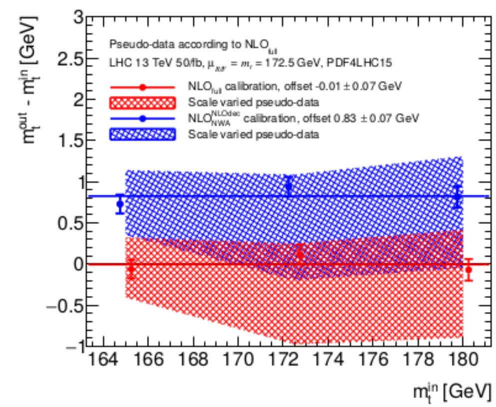

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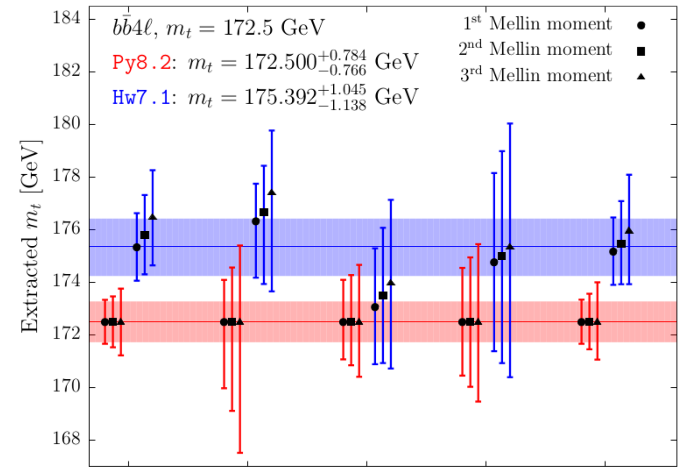

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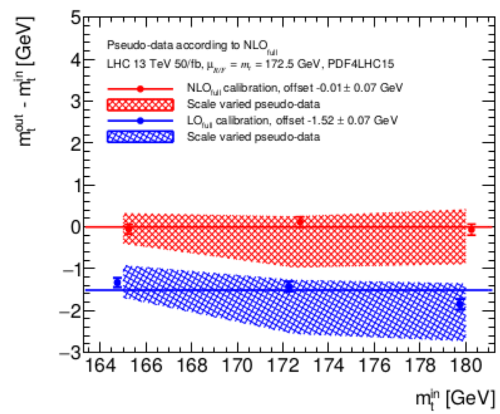
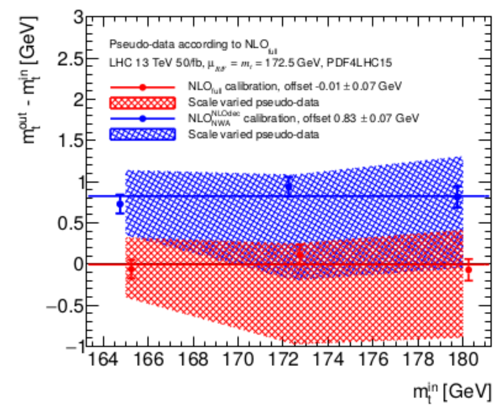
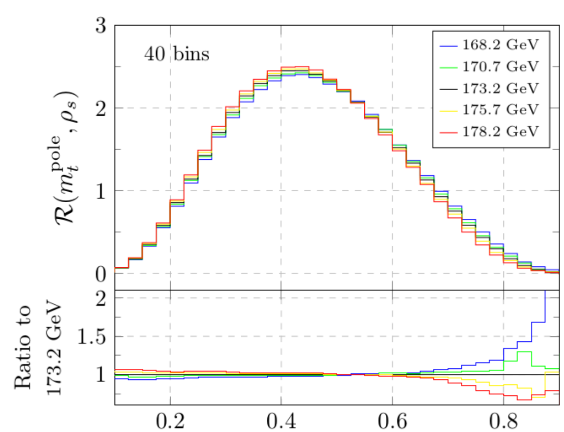




Journal of High Energy Physics
March 2018, 2018:169 | Cite as

Top quark mass studies with $t\bar{t}j$ at the LHC

Authors Authors and affiliations
G. Bevilacqua, H. B. Hartanto, M. Kraus, M. Schulze, M. Worek



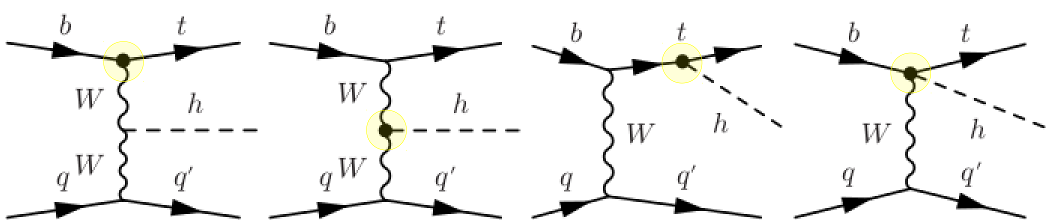
Theory, NLO QCD CT14 PDF	$m_t^{out} \pm \delta m_t^{out}$ [GeV]	$m_t^{in} - m_t^{out}$ [GeV]
	31 bins	
Full, $\mu_0 = H_T/2$	173.09 ± 0.42	+0.11
Full, $\mu_0 = E_T/2$	172.45 ± 0.39	+0.75
Full, $\mu_0 = m_t$	173.76 ± 0.40	−0.56
NWA, $\mu_0 = m_t$	175.65 ± 0.31	−2.45
$NWA_{Prod.}$, $\mu_0 = m_t$	169.59 ± 0.30	+3.61

Top-Higgs coupling

Single-top associated production with a Z or H boson at the LHC: the SMEFT interpretation

(Apr 2018)

Celine Degrande,[a] Fabio Maltoni,[b] Ken Mimasu,[b] Eleni Vryonidou,[a] Cen Zhang[c]



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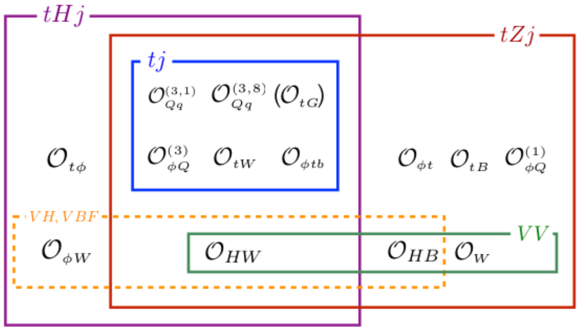

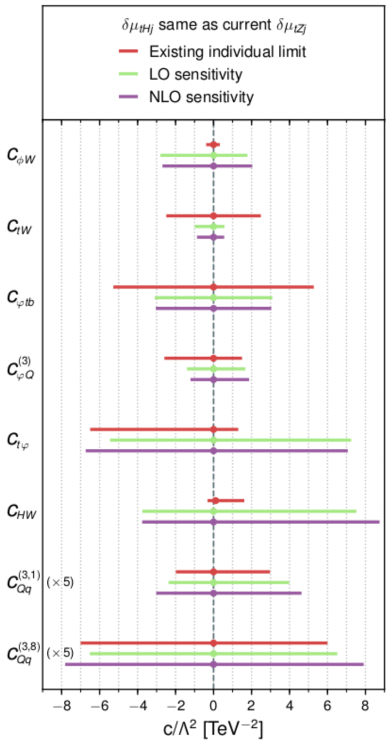

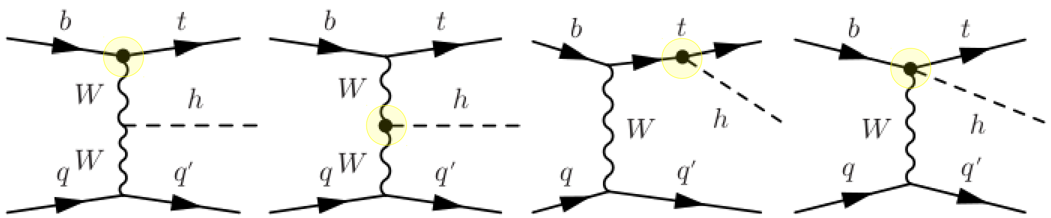

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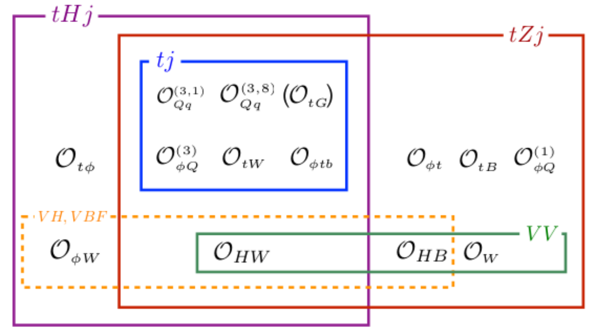
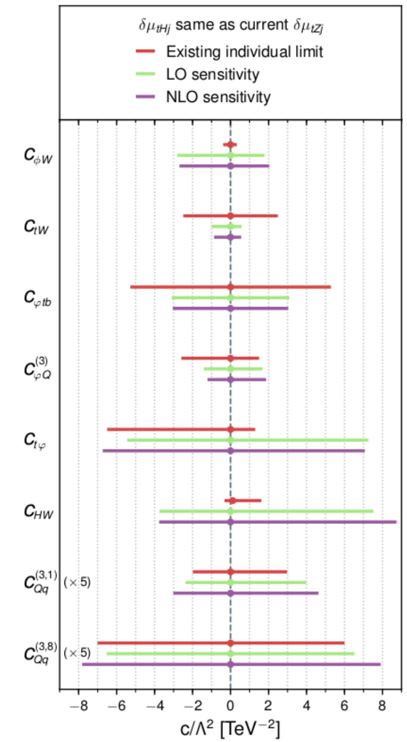
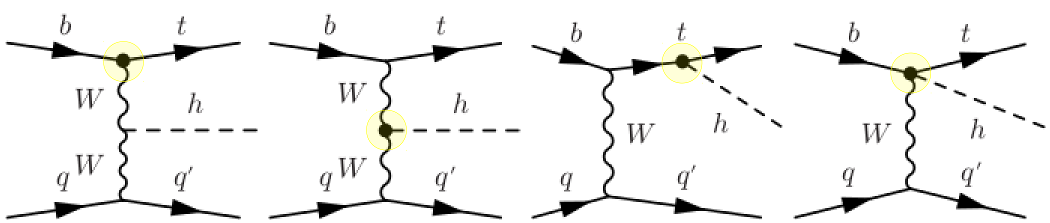


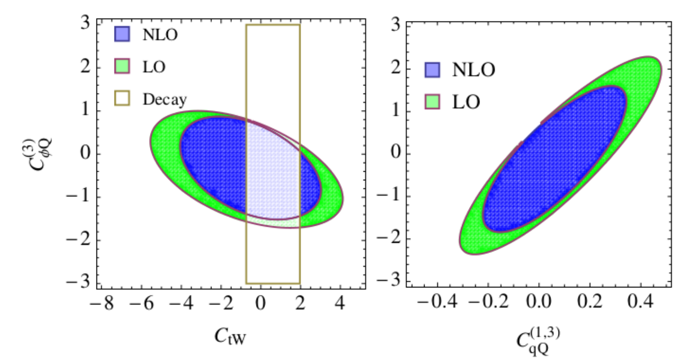


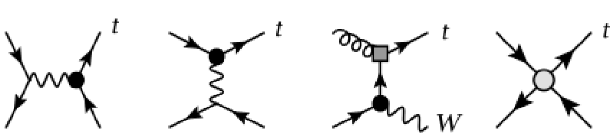


Single Top Production at Next-to-Leading Order in the Standard Model Effective Field Theory

Cen Zhang

Phys. Rev. Lett. **116**, 162002 – Published 21 April 2016





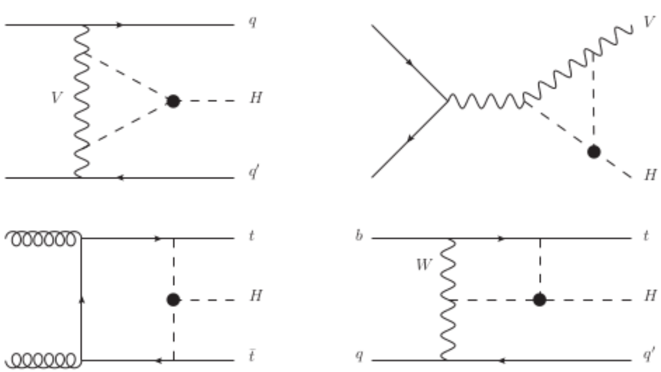
Top-Higgs coupling

The European Physical Journal C
December 2017, 77:887 | Cite as

Trilinear Higgs coupling determination via single-Higgs differential measurements at the LHC

Authors Authors and affiliations

Fabio Maltoni, Davide Pagani, Ambresh Shivaji, Xiaoran Zhao



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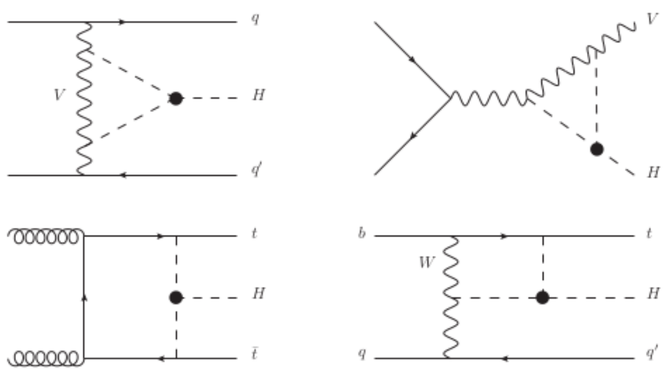

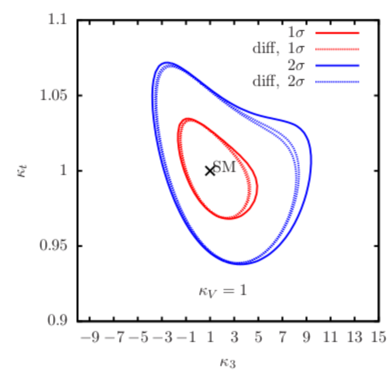

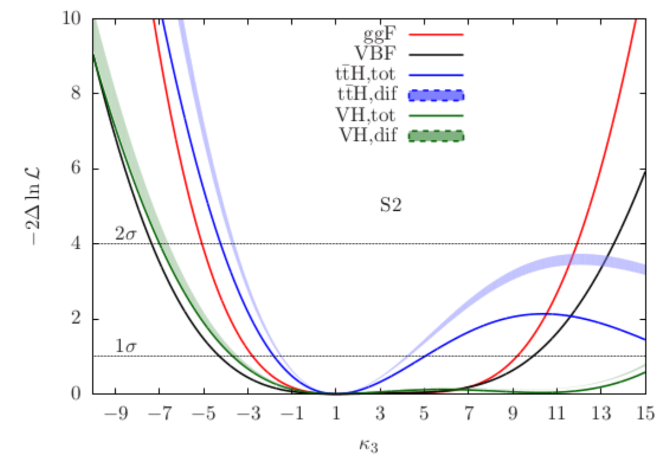

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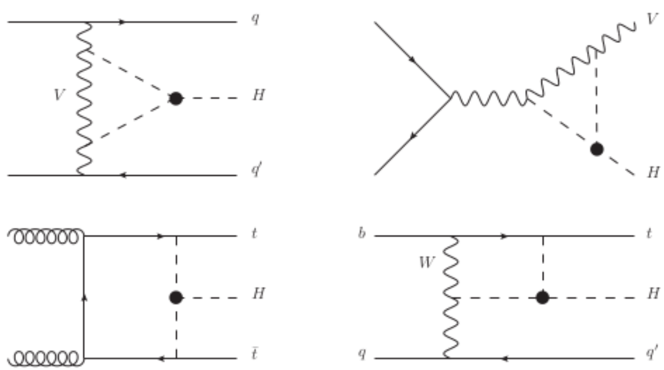

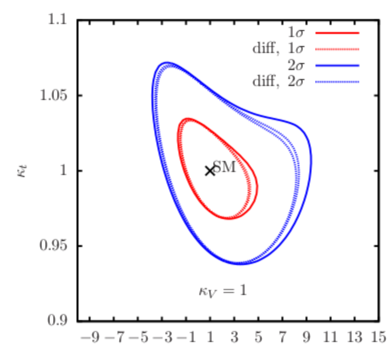

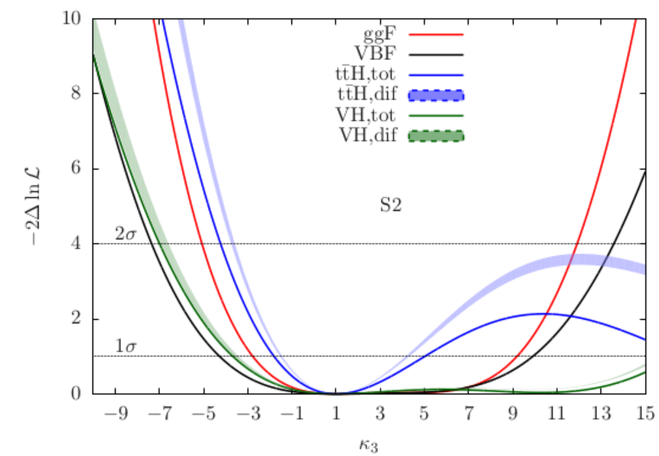

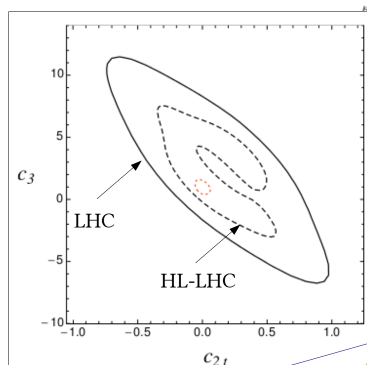

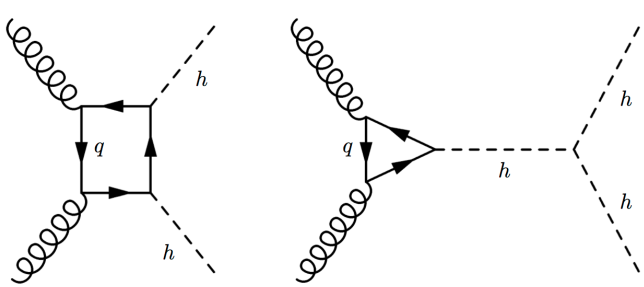

Effective field theory analysis of double Higgs boson production via gluon fusion

Aleksandr Azatov, Roberto Contino, Giuliano Panico, and Minho Son
Phys. Rev. D 92, 035001 – Published 4 August 2015

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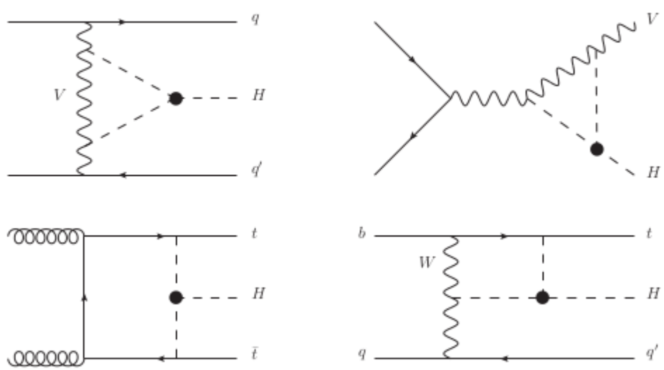
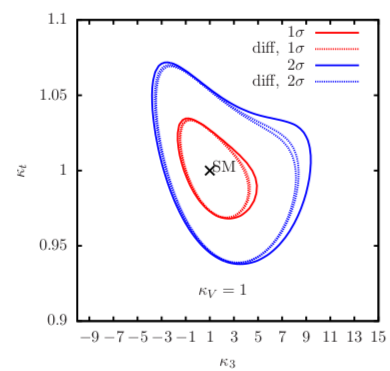
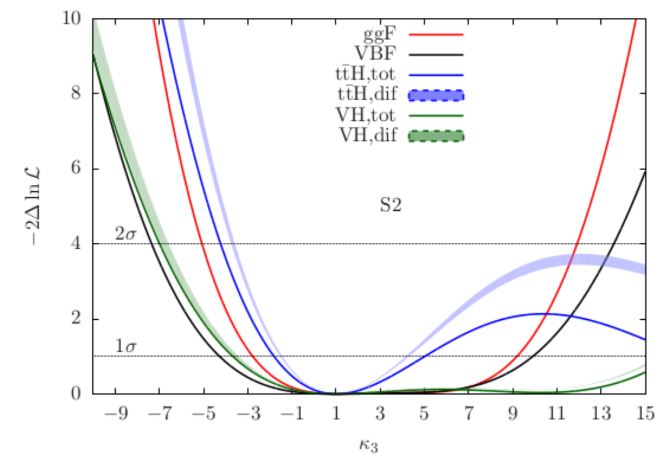




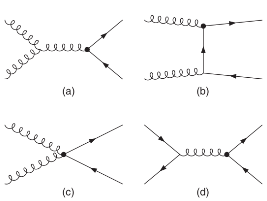


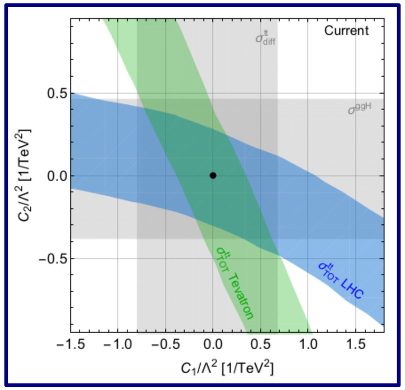
Constraints on top quark nonstandard interactions from Higgs boson and $t\bar{t}$ production cross sections

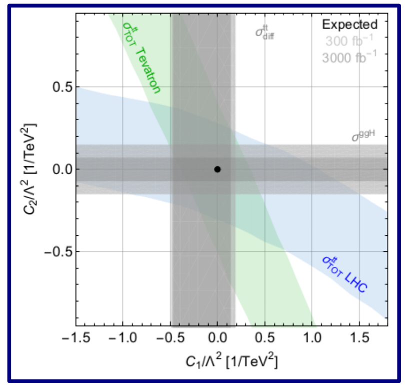
D. Barducci, M. Fabbrichesi, and A. Tonero
Phys. Rev. D **96**, 075022 – Published 16 October 2017

$$\mathcal{O}_1 = \frac{C_1}{\Lambda^2} \bar{t}\gamma^\mu T^a t D^\nu G^a_{\mu\nu}$$

$$\mathcal{O}_2 = \frac{C_2}{\Lambda^2} v\bar{t}\sigma^{\mu\nu} T^a t G^a_{\mu\nu},$$





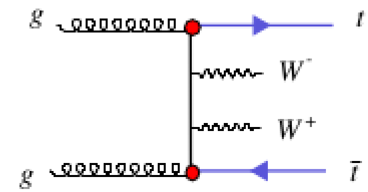


Electroweak top quark couplings

Study of top quark dipole interactions in $t\bar{t}$ production associated with two heavy gauge bosons at the LHC

Seyed Mohsen Etesami, Sara Khatibi, and Mojtaba Mohammadi Najafabadi

Phys. Rev. D **97**, 075023 – Published 17 April 2018



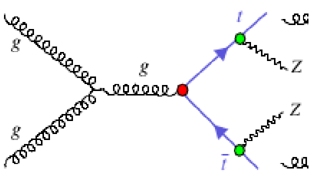


Table 6: Limits on $d_V^{g,Z}$ and $d_A^{g,Z}$ at 95% CL corresponding to 30, 300, and 3000 fb^{-1} integrated luminosities.

Coupling	30 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
d_V^g	[-0.023,0.026]	[-0.012,0.015]	[-0.006,0.009]
d_A^g	[-0.024,0.024]	[-0.013,0.013]	[-0.007,0.007]
d_V^Z	[-0.22,0.21]	[-0.12,0.11]	[-0.07,0.06]
d_A^Z	[-0.21,0.21]	[-0.11,0.11]	[-0.06,0.06]

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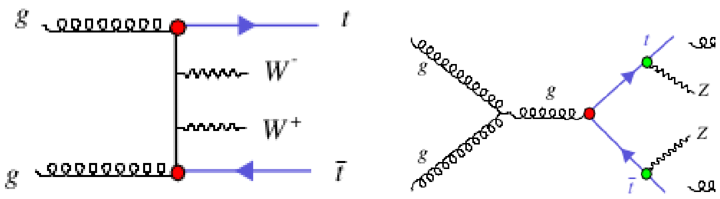

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d_V^Z	[-0.22,0.21]	[-0.12,0.11]	[-0.07,0.06]
d_A^Z	[-0.21,0.21]	[-0.11,0.11]	[-0.06,0.06]

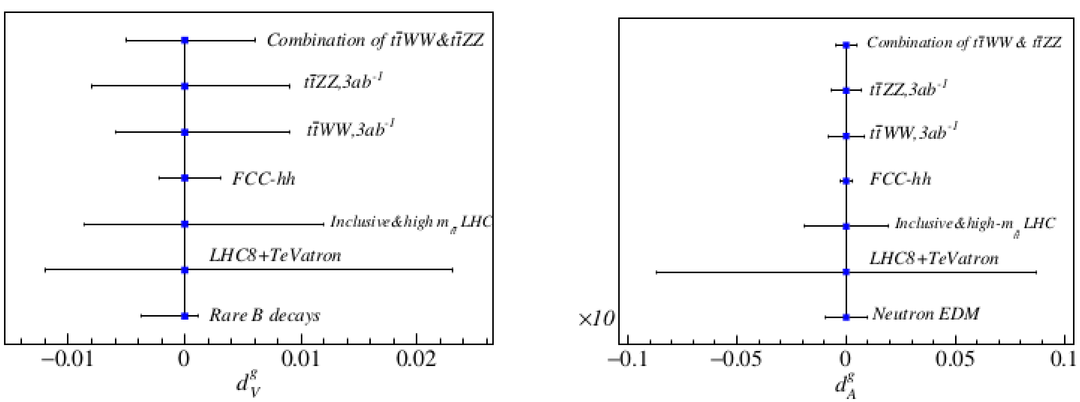

Figure 3: The limits at 95% CL on d_V^g (right panel) and on d_A^g (left panel) from $t\bar{t}WW$ (same-sign leptons) and $t\bar{t}ZZ$ (four-lepton) with 300 and 3000 fb^{-1} are shown. The indirect limits on d_A^g (neutron electric dipole moment) and on d_V^g (rare B meson decays) are presented as well as the limits from the combination of $t\bar{t}$ cross section at the LHC8 and Tevatron. Also, the limits which could be derived from tail of $t\bar{t}$ mass spectrum at the FCC-hh and LHC are shown.

Community effort: Setting Standards

Interpreting top-quark LHC measurements in the standard-model effective field theory

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T. Plehn,[18] F. Riva,[2] M. Russell,[18] J. Santiago,[19] M. Schulze,[13] Y. Soreq,[20]
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Four-quark operators:

$$O_{qq}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{q}_k\gamma_\mu q_l), \quad (1)$$

$$O_{qq}^{3(ijkl)} = (\bar{q}_i\gamma^\mu\tau^I q_j)(\bar{q}_k\gamma_\mu\tau^I q_l), \quad (2)$$

$$O_{qu}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{u}_k\gamma_\mu u_l), \quad (3)$$

$$O_{qu}^{8(ijkl)} = (\bar{q}_i\gamma^\mu T^A q_j)(\bar{u}_k\gamma_\mu T^A u_l), \quad (4)$$

$$O_{qd}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{d}_k\gamma_\mu d_l), \quad (5)$$

$$O_{qd}^{8(ijkl)} = (\bar{q}_i\gamma^\mu T^A q_j)(\bar{d}_k\gamma_\mu T^A d_l), \quad (6)$$

$$O_{uu}^{(ijkl)} = (\bar{u}_i\gamma^\mu u_j)(\bar{u}_k\gamma_\mu u_l), \quad (7)$$

$$O_{ud}^{1(ijkl)} = (\bar{u}_i\gamma^\mu u_j)(\bar{d}_k\gamma_\mu d_l), \quad (8)$$

$$O_{ud}^{8(ijkl)} = (\bar{u}_i\gamma^\mu T^A u_j)(\bar{d}_k\gamma_\mu T^A d_l), \quad (9)$$

$$^\ddagger O_{quqd}^{1(ijkl)} = (\bar{q}_i u_j)\,\varepsilon\,(\bar{q}_k d_l), \quad (10)$$

$$^\ddagger O_{quqd}^{8(ijkl)} = (\bar{q}_i T^A u_j)\,\varepsilon\,(\bar{q}_k T^A d_l), \quad (11)$$

Two-quark operators:

$$^\ddagger O_{u\varphi}^{(ij)} = \bar{q}_i u_j \tilde{\varphi}\,(\varphi^\dagger\varphi), \quad (12)$$

$$O_{\varphi q}^{1(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_i\gamma^\mu q_j), \quad (13)$$

$$O_{\varphi q}^{3(ij)} = (\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{q}_i\gamma^\mu\tau^I q_j), \quad (14)$$

$$O_{\varphi u}^{(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_i\gamma^\mu u_j), \quad (15)$$

$$^\ddagger O_{\varphi ud}^{(ij)} = (\tilde{\varphi}^\dagger iD_\mu\varphi)(\bar{u}_i\gamma^\mu d_j), \quad (16)$$

$$^\ddagger O_{uW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I u_j)\,\tilde{\varphi}W^I_{\mu\nu}, \quad (17)$$

$$^\ddagger O_{dW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I d_j)\,\varphi W^I_{\mu\nu}, \quad (18)$$

$$^\ddagger O_{uB}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}u_j)\quad\tilde{\varphi}B_{\mu\nu}, \quad (19)$$

$$^\ddagger O_{uG}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}T^A u_j)\,\tilde{\varphi}G^A_{\mu\nu}, \quad (20)$$

Two-quark-two-lepton operators:

$$O_{lq}^{1(ijkl)} = (\bar{l}_i\gamma^\mu l_j)(\bar{q}_k\gamma^\mu q_l), \quad (21)$$

$$O_{lq}^{3(ijkl)} = (\bar{l}_i\gamma^\mu\tau^I l_j)(\bar{q}_k\gamma^\mu\tau^I q_l), \quad (22)$$

$$O_{lu}^{(ijkl)} = (\bar{l}_i\gamma^\mu l_j)(\bar{u}_k\gamma^\mu u_l), \quad (23)$$

$$O_{eq}^{(ijkl)} = (\bar{e}_i\gamma^\mu e_j)(\bar{q}_k\gamma^\mu q_l), \quad (24)$$

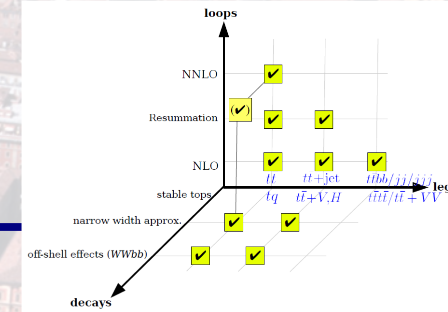
$$O_{eu}^{(ijkl)} = (\bar{e}_i\gamma^\mu e_j)(\bar{u}_k\gamma^\mu u_l), \quad (25)$$

$$^\ddagger O_{lequ}^{1(ijkl)} = (\bar{l}_i e_j)\,\varepsilon\,(\bar{q}_k u_l), \quad (26)$$

$$^\ddagger O_{lequ}^{3(ijkl)} = (\bar{l}_i\sigma^{\mu\nu}e_j)\,\varepsilon\,(\bar{q}_k\sigma_{\mu\nu}u_l), \quad (27)$$

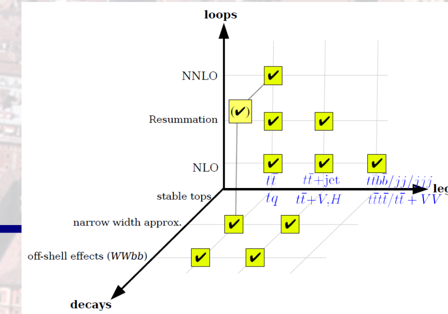
$$^\ddagger O_{ledq}^{(ijkl)} = (\bar{l}_i e_j)(\bar{d}_k q_l), \quad (28)$$

SUMMARY



- **Incredible progress on all fronts: LHC, detector experiments & theory**
- **Top quark physics is particularly thriving**

SUMMARY



- Incredible progress on all fronts: LHC, detector experiments & theory
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- State-of-the-art OR near future:

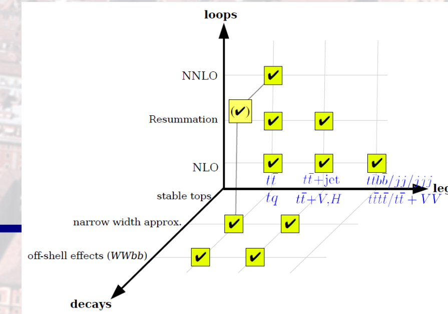
  single top, ttbar: NNLO QCD+ NLO EW in production and decay (NWA)

  single top, ttbar, ttbar+X: NLO with off-shell effects

  single top, ttbar, ttbar+X: NLO beyond SM,

  Exploration of on-shell vs. loop sensitivity

SUMMARY



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  Exploration of on-shell vs. loop sensitivity

- **Future challenges:**

  Exp. uncertainties often smaller than theor. systematics, already now

  Improving precision on *ttbar* below 5% precision

  NNLO for *ttbar+X*: 2-loop and 1-loop-real corrections